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EAGLE, A 2 TW PULSED POWER RESEARCH FACILITY*

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Abstract

EAGLE is an experimental pulse generator designed and built at Physics International Company (PI) for research in high-power switching, pulse compression, power flow, magnetic insulation, and dielectric breakdown. EAGLE is a wedge-shaped 1/20th "slice" (module) of ROULETTE, PI's conceptual design for a 40 to 50 TW, disk-shaped, modular accelerator designed to drive imploded plasma or particle beam loads. EAGLE's nominal design goals were a 100 ns, 2 TW, 2 MV, 1 MA pulse into a resistive load, or a 150 to 200 ns pulse at lower power. EAGLE has a 0.9 MJ Marx generator and four water-dielectric triplate transmission lines with adjustable impedances. The first line is a gas-switched transfer capacitor. Next are two water-switched pulsed compression stages and an output line converging to either a resistive load or a racetrack-shaped water-vacuum interface. We discuss the ROULETTE conceptual design, describe EAGLE, outline planned research on EAGLE, and summarize some of the program's technology developments.

Introduction

EAGLE is part of a Defense Nuclear Agency program to expand our technology base in pulsed power.[1] The overall program is directed toward developing a very intense source of pulsed X-rays with photon energies of a few keV to simulate nuclear weapon effects. Over the last five years, generator-driven imploded plasmas have emerged as the most promising candidate for supplying such a radiation source. Research in this concept is now underway at Physics International Company (PI),[2,3] Maxwell Laboratories (MLI),[4] Sandia National Laboratories, Albuquerque (SNLA),[5] the Air Force Weapons Laboratory (AFWL),[6] and in the Soviet Union.[7] Future research is planned at the Atomic Weapons Research Establishment (AWRE), Aldermaston, England.[8] Research to date indicates that very large pulsed-power drivers will be required to produce the radiation needed to expose full-scale military systems to the threat level.

The driver size for a full-scale radiation simulator has been estimated by extrapolating radiation yield curves obtained from imploded plasma measurements at 1 to 12 TW. The results indicate that a 100 ns driving pulse of ⩾ 100 TW (10 MJ) will be required. Pulse parameters would be approximately 2 MV, 50 MA. But before a driver with these characteristics is built, experiments at an intermediate level are needed to verify the radiation scaling measurements made at lower power. PI has developed a conceptual design for an accelerator for such experiments which would produce roughly half the output of the full-radiation simulator. We call the design ROULETTE.

ROULETTE is shown in Figure 1. Its approximate pulse parameters are 40-50 TW, 4-5 MJ, 20-22 MA, 2-2.5 MV, 100 ns. The system would consist of 20 water dielectric, triplate pulse-forming modules arranged into a 30-m-diameter disk. Surrounding the disk is a ring of oil-immersed Marx generators which store 12 to 15 MJ. Energy is fed from the Marx generators to the waterlines, which form and converge the pulse radially inward until the water-breakdown limit on power flow in water is reached, about 2.5 to 3.0 m from the axis of the disk. Each module then injects its pulse through a racetrack-shaped insulator into a magnetically insulated, triplate feed, where the combined pulse is further compressed, then fed through a convolute to the plasma load on axis. Radiation is taken from above the disk.

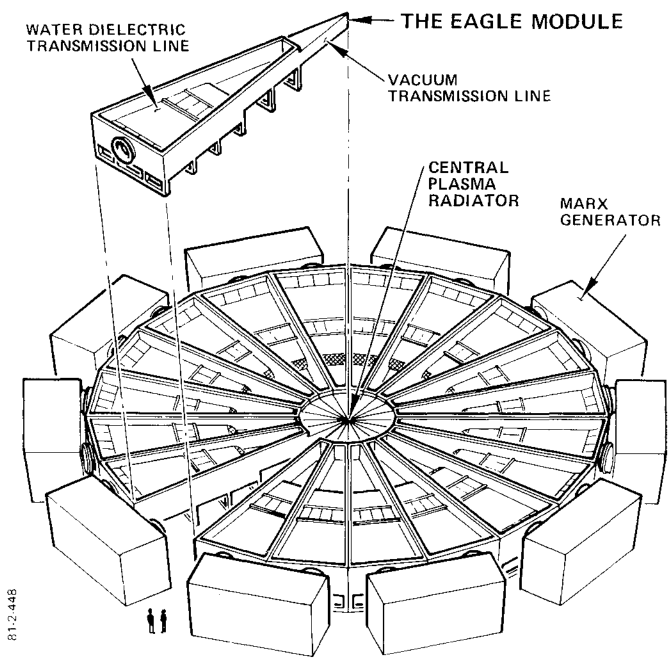

Figure 1 The ROULETTE accelerator system.

The ROULETTE design incorporates much of the pulsed power technology developed over the last 10 years at PI and elsewhere. Early machines like GAMBLE II (NRL)[9] and OWL II (PI)[10] established the basic principles of Marx-generator-driven, water-dielectric pulse-forming lines as cost-effective, low-impedance generators. Later, machines like PITHON[11] at PI, the BLACKJACK[12] series at MLI, and PROTO II[13] at SNLA demonstrated staged pulse-compression in water using untriggered, multiple-site water switches.[14] PBFA-1 has demonstrated the feasibility of synchronously operating multiple modules at the 30 TW, 1 MJ level[15] for driving particle beam loads. But ROULETTE will require somewhat different technology because of its high pulse energy (up to 5 MJ), and because of the need to drive single imploded plasma loads.

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14. ABSTRACT **EAGLE is an experimental pulse generator designed and built at Physics International Company (PI) for research in high-power switching, pulse compression, power flow, magnetic insulation, and dielectric breakdown. EAGLE is a wedge-shaped 1/20th "slice" (module) of ROULETTE, PI's conceptual design for a 40 to 50 TW, disk-shaped, modular accelerator designed to drive imploded plasma or particle beam loads. EAGLE's nominal design goals were a 100 ns, 2 TW, 2 MV, l MA pulse into a resistive load, or a 150 to 200 ns pulse at lower power. EAGLE has a 0.9 MJ Marx generator and four water-dielectric triplate transmission lines with adjustable impedances.**					
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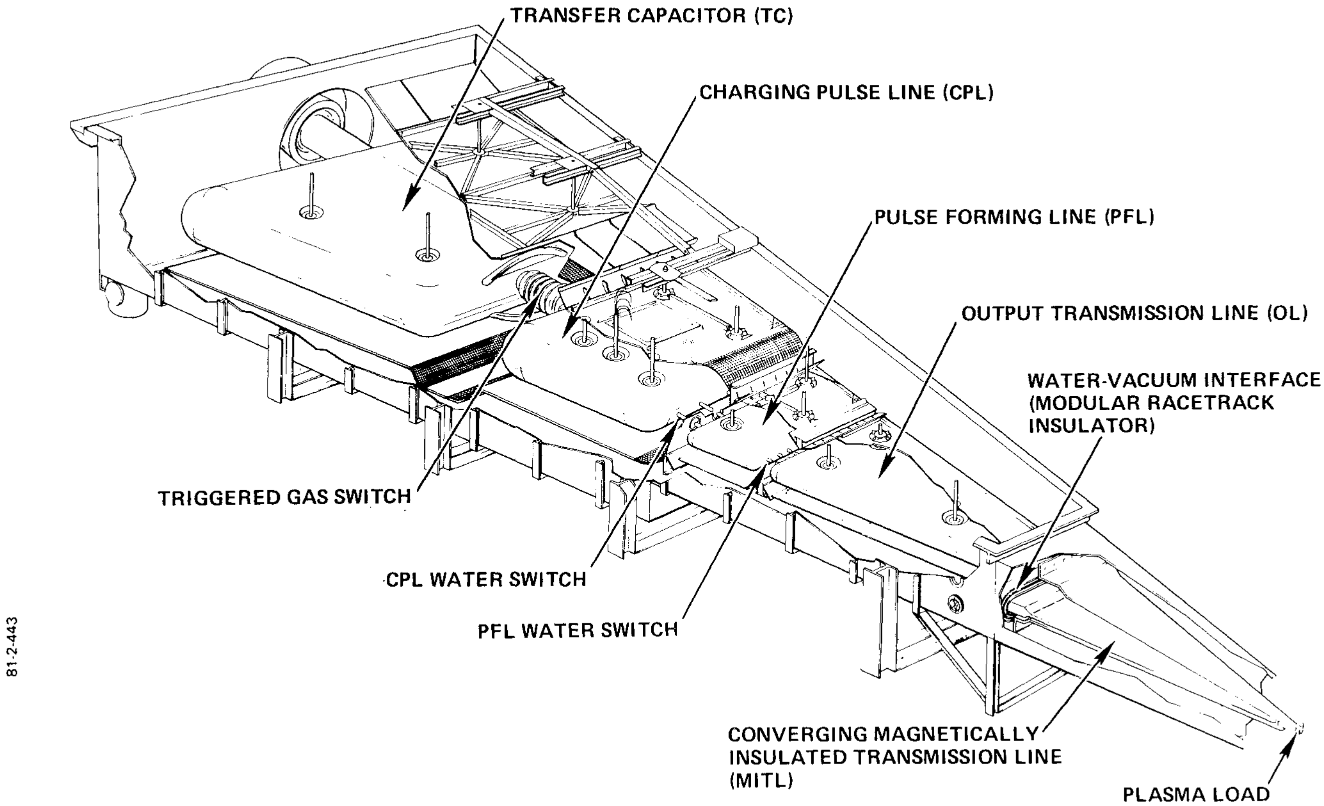

Figure 2 EAGLE waterlines.

EAGLE has been built to address ROULETTE technology questions. EAGLE represents a 1/20th "slice" of ROULETTE, like the elevated module shown in Figure 1. In the following paragraphs, we describe EAGLE, discuss how some of the research areas relate to ROULETTE, and summarize some of the program's technology developments.

EAGLE System Description

EAGLE is nominally a 2 TW, 200 kJ, 2 MV, 100 ns pulse generator with an output impedance of 2 Ω. But its output characteristics can be varied substantially by making adjustments in the waterlines. The Marx-generator-driven waterlines are shown in Figure 2. All energy-handling components are housed in a wedge-shaped, 66,000 liter, stainless steel tank, which confines them to an 18° sector, in keeping with the ROULETTE design of Figure 1. The 2.4-m-high tank is nearly 5 m wide at the rear and converges over a distance of 12.6 m to a width of just over 1 m at the front. A 0.9 MJ Marx generator connects to the first waterline at the rear of the tank. The front of the tank is designed to accept a modular, racetrack-shaped, water-vacuum interface which would connect to a magnetically insulated vacuum feed. For waterline experiments, a resistive load (not shown) has been installed.

Inside the tank are three switched pulse-compression stages: a Marx-generator-driven transfer capacitor (TC), a charging pulseline (CPL), and a pulse-forming line (PFL). At the forward ends of the TC, CPL, and PFL are a triggered gas switch (TGS) and two untriggered, multiple-site water switches. A converging output line (OL) delivers the pulse to either the resistive load or the vacuum insulator.

All EAGLE waterlines are bounded triplate transmission lines. Construction is simple and rugged. Main electrode surfaces are flat plates of 0.5-cm-thick stainless steel. The plates are pop-riveted to space frames to permit replacement if they are badly deformed during high-power experiments. The outer (ground) electrodes are adjustable to allow for impedance variations. The impedance adjustment ranges, shown in Table 1, can be increased with minor modifications.

Table 1 EAGLE waterline impedance variations.

Line		Adjustment Range (Ω)
Transfer Capacitor		1.37 - 1.55
Charging Pulseline	Input:	1.06-1.62
	Output:	1.27-1.71
Pulse-Forming Line	Input:	0.95-1.73
	Output:	1.00-1.71
Output Line	Input:	1.07-1.74
	Output:	1.79-2.25

When EAGLE's waterlines are set for nominal impedances, the calculated circuit response into a matched, resistive load is as shown in Figure 3. When the circuit elements in the figure are viewed as lumped elements, each successive energy transfer stage is capacitively undermatched to provide a voltage ring-up. The voltage ring-up compensates for switch losses and shunt conductances. This scheme allows each of the three high-power switches to operate at roughly the same voltage, in the range 2.5-3.0 MV. The converging geometry of EAGLE also helps to keep impedances similar without using excessive line lengths. The TC and OL have essentially the same impedance, and differ by only 15% in voltage. Losses and jitter are reduced because the switches are operated at reduced voltages.

Figure 3 shows only the 100 ns pulse mode for EAGLE. A longer (~ 170 ns), lower-power pulse can be

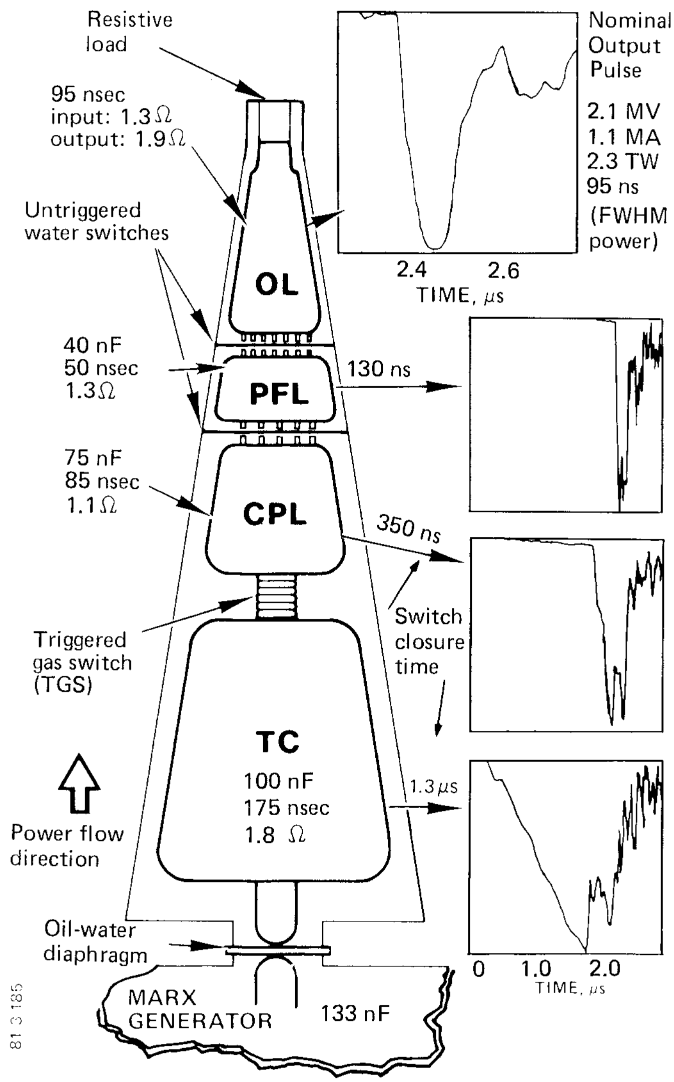

Figure 3 EAGLE circuit response. Waveforms are computer-calculated voltages for one set of circuit conditions. The output pulse is voltage into a matched, resistive load.

produced by using the 85 ns (one-way transit) CPL as a pulse-forming line. In either pulse mode, EAGLE output characteristics can be varied by using adjustments designed into the machine.

EAGLE is also designed to test the limits of power flow in water. Every line can be stressed to beyond breakdown, as defined by[16]

$$\bar{E} = 0.23\ t^{-1/3}\ A^{-0.058} \tag{1}$$

where $\bar{E}$ is the breakdown field in MV/cm, t is the time in μs that pulses exceed 0.63 of their maxima, and A is electrode area in cm^2. We will be able to selectively overstress lines by using the adjustments of Table 1.

Marx Generator

EAGLE has two Marx generators (see Figure 4) located in a single 100 m^3 oil tank. Incorporating one hundred 3.2 μF, 75 kV capacitors, and 50 triggered SF_6 spark gaps, the Marxes can store 0.94 MJ at full charge. Erected capacitance is 133 nF, and full open-circuit voltage is 3.8 MV. Cross-coupling between Marxes is minimized by placing their grounded ends near opposite tank walls. Discharge current from each Marx flows through separate series resistors to a common feed. The feed pierces a single 1.4-m-diameter urethane, oil/water interface, then connects to the 100 nF TC. Because the Marx capacitors and spark gaps are configured for low inductance, the TC can be fully charged in 1.6 μs.

EAGLE's low-inductance Marx circuit arrangement is similar to that of PBFA-1 at SNLA,[15] but EAGLE stores more energy per unit volume because of an advanced capacitor design. The capacitors (Aerovox Model SX160E11) are made with eight series, extended-foil sections of paper/polypropylene/dioctyl phthalate (DOP). Since each section can operate at 4573 V/mil, each capacitor can store 9.4 kJ in a standard, LASL "Scyllac"[17] can. The energy density of a single Marx generator is 54 kJ/m^3. If the volume of insulating oil is included, the entire system stores 9.4 kJ/m^3.

To construct EAGLE spark gaps, a novel technique was developed. Endplates and electrodes are made of a single, nonporous brass casting. In the standard version of the spark gap (PI Model T-508), which PI

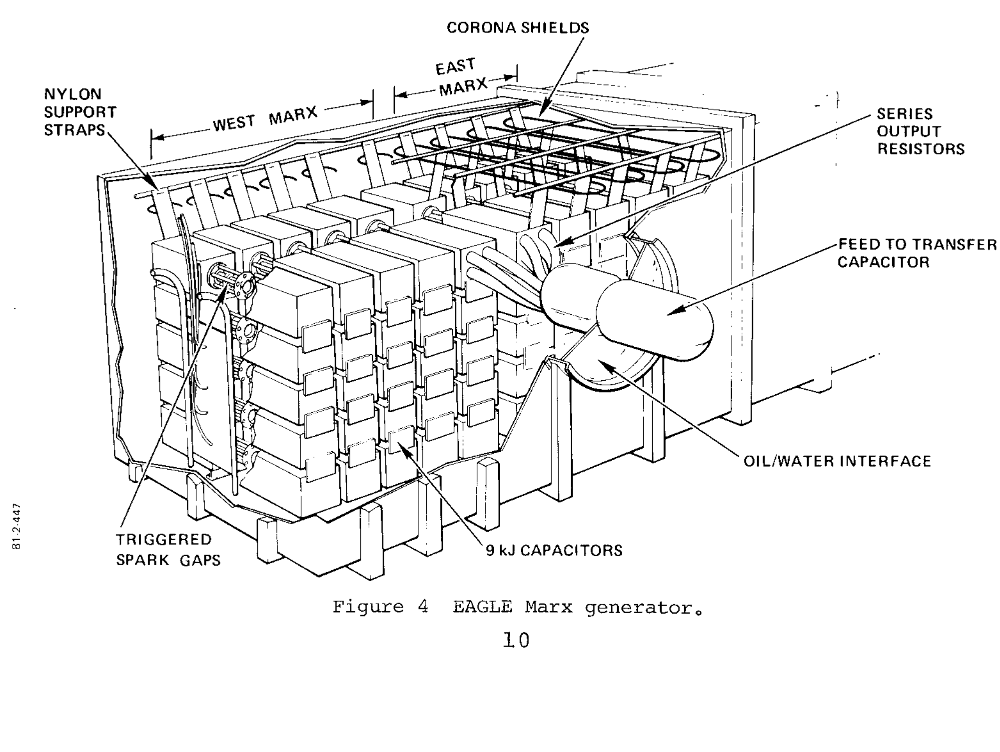

Figure 4 EAGLE Marx generator.

developed for the AURORA accelerator[18] over ten years ago, electrodes are attached to endplates using metal studs and compressible current contacts. The experimental EAGLE version of the switch has eliminated current contacts, and should prove to be more reliable. In EAGLE, each switch will withstand 150 kV dc, conduct 160 kA, and transfer 0.4 C.

Construction and testing of the EAGLE Marx generators is complete. Performance is excellent. Erection is possible at as low as 25-30% of single-gap self-fire (better than 3:1 triggering range), and shot-to-shot rms jitter for a single Marx is less than 10 ns (rms) at a constant ± 45 kV charge voltage over a spark gap pressure range of 1.3-2.7 atm abs. For both Marx generators in parallel, the measured inductance is 4.28 μH, including ground connections and the output feed. Inductance of a single 18 kJ, 150 kV stage averages 300 nH.

Triggered Gas Switch

The ROULETTE conceptual design needs low-jitter switches between the TC and CPL stages to ensure synchronous module output. To satisfy this need, 20 triggered gas switches (TGS) are used, one for each module in the system. The TGS concept affords the advantages of low jitter, small resistive losses, minimal capacitive effects, low acoustic shock, and well-controlled current distribution. Because the TGS concept is very important for the ROULETTE design, we conducted a program to develop a prototype[19] prior to the design and construction of EAGLE.

The EAGLE prototype TGS is shown in Figure 5. It is a multistage, UV-illuminated SF_6 switch approximately 75 cm long by 40 cm in diameter. There are six stages. Each stage has a pair of toroidal, brass electrodes with annular slits that transmit UV radiation to downstream stages as the switch progressively closes. The closure sequence starts with a 150-200 kV pulse applied to circuitry within the switch which triggers a midplane electrode in the first stage.

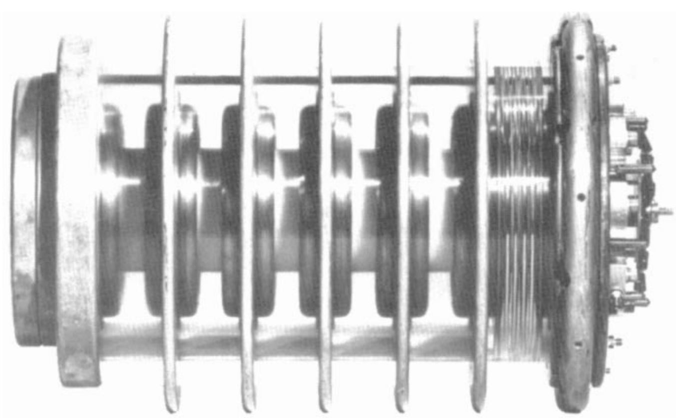

Figure 5 EAGLE six-stage prototype triggered gas switch.

Performance of the prototype TGS is excellent. Tests were conducted on the OWL generator at PI[10] and on the SUPERMITE facility at SNLA[20] at voltage, current, and charge transfer values of up to 3.0 MV, 525 kA, 0.25 C with switchout times of 0.7-1.2 μs. Jitter was < 2 ns (1σ) at approximately 75% of the self-break voltage.

Further experiments using our TGS concept are planned for EAGLE. For EAGLE, two stages were added to the prototype, and a new trigger package was developed. The trigger package, a fiber-optic-controlled, immersible unit designed to operate under water, is described elsewhere in these proceedings.[21] The EAGLE experiments will use the new trigger package to control the new eight-stage TGS at full ROULETTE operating levels, up to 3.2 MV and 0.7 MA, with a switchout time of 1.3 μs.

Water Switches

EAGLE's two self-breaking water switches are at the output end of the CPL and PFL. Both switches have discrete, multiple electrodes, which extend through prepulse-suppressing ground planes, or "prepulse shields."[22] Features are built into the switch regions to accommodate optimization experiments and EAGLE's pulse mode variability.

A cross section of the CPL switch region is shown in Figure 6. To accommodate line spacing variations in the CPL, the upper and lower ground electrodes are connected to the prepulse shield with flexible stainless steel mesh. On the PFL side of the shield, outer connections are made with spring-loaded "flappers" which contact the PFL outer electrodes. The shield, which capacitively decouples the CPL from the PFL to suppress PFL prepulse, has five 7.6-cm-diameter holes. By removing inserts, the holes can be enlarged to 12.7 cm for operation at higher voltage.

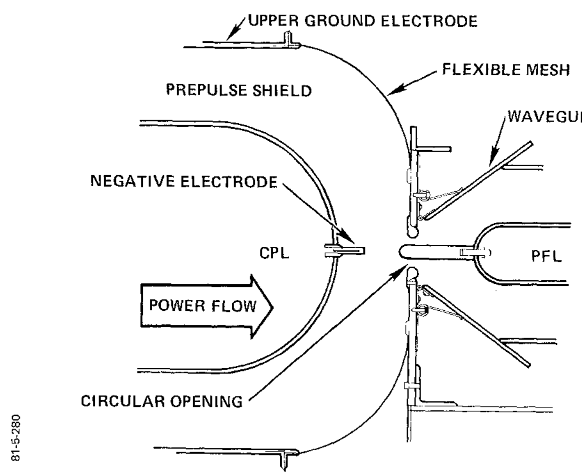

Figure 6 EAGLE CPL water switch region. Cross section in the vertical plane of EAGLE's long axis.

The CPL switch design parameters are 2.8-3.3 MV and 0.8-1.2 MA, with switchout times of 300-350 ns. One, two, three, or five symmetrically arranged switch sites can be used to vary switch inductance during circuit optimization experiments.

The PFL switch region is shown in Figure 7. Its design parameters are 3.0 MV and 1.4 MA, with a switchout time in the range of 80-130 ns. PFL switch geometry is similar to that of the CPL switch. Flappers are used on both sides of the prepulse shield, and multiple-site, negatively enhanced electrodes are mounted on the end of the PFL. However, rather than using discrete circular openings in the prepulse shield, we designed a variable spacing slot (like a straight-bladed guillotine). The slot, which has a spacing variability range of 7.6-22.8 cm, allows us to use an arbitrary number of switch sites, up to and including a continuous blade.

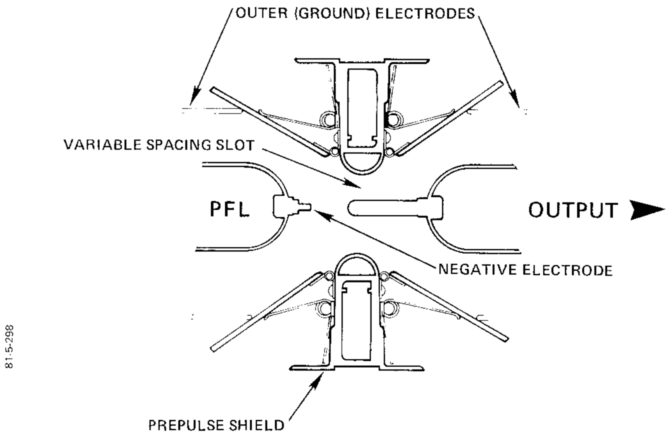

Figure 7 EAGLE PFL water switch region.

The electrode tips of both the PFL and CPL switches are field-enhanced, so breakdown streamer channels originate from the negative side. To determine the electrode spacing, d, we used a negative streamer velocity relation suggested by J. C. Martin[23] in 1977,

$$\bar{u}\, t^{1/2} = 10\ V \qquad (3)$$

where $\bar{u} = d/t$ in cm/μs, t is the time in μs, during which the voltage is above 0.63 V, and V is the breakdown voltage in MV. Martin suggested this approximate relation after studying water switch data from several laboratories.[14,24,25] Prior to designing the EAGLE switches, we cross-checked Martin's relation by using data from an experiment on negatively enhanced ground-plane-shielded switches at PI.

Figure 8 summarizes the comparison between the PI data and Martin's relation, expressed as an average switching field, V/d, as a function of t. The data

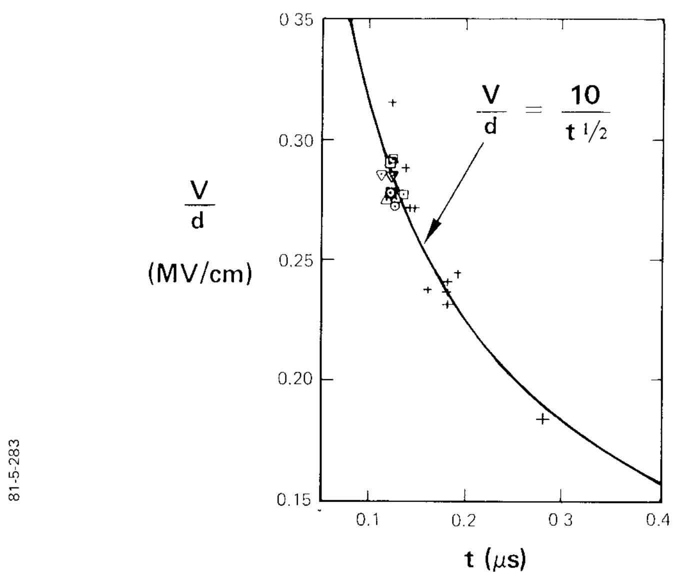

Figure 8 J. C. Martin's water streamer velocity relation compared to PI data. Data base was 21 shots; various symbols denote different spacings over the range 11.0 to 18.3 cm.

base was 21 shots and covered the experimental ranges of 3.0-5.8 MV, 0.11-0.28 μs, and 11.0-18.3 cm, roughly a factor-of-two variation in each parameter. To compare the data, we expressed Martin's formula in terms of a figure of merit

$$\frac{\bar{u}\, t^{1/2}}{V} = \text{FOM (= 10 according to Martin).} \qquad (2)$$

The data of Figure 8 give FOM = 10.03 ± 0.41 (4.1%). Agreement is obviously excellent. Miller reports that a wide range of data from MLI also support Martin's relation.[26]

There are two purposes for the flapper plates shown in Figures 6 and 7. One purpose is to make moveable current contacts to the adjustable outer (ground) electrodes. The other purpose is to allow us to test a new switching concept that exploits transmission line reflections in the PFL. The concept, suggested by Ian Smith[27] in 1978, is illustrated in Figure 9. We call it "double-bounce" switching.

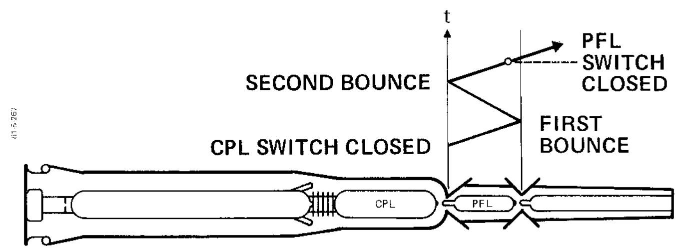

Figure 9 Double-bounce switching.

In principle, double-bounce switching can allow extraction of peak power in excess of the theoretical $V^2/4Z$ limit from an ideal transmission line. If it works, the CPL and PFL can be operated at a lower stress, and PFL switch loss and jitter will be reduced. The technique works when a line like the CPL charges a PFL such that a well defined charging wave is doubly reflected, first from the open PFL switch, then from the CPL switch inductance. The PFL switch is closed just prior to arrival of the re-reflected pulse, at a time ~ $3\ell/c$ after the CPL switch was closed, where ℓ is the PFL length and c is the speed of light in water.

2-D equivalent circuit calculations indicate that under certain conditions, double-bounce switching could enhance output power by 50-60% over the $V^2/4Z$ theoretical limit. For our calculations, when $\ell' = 1.7\ \ell$ (CPL length, ℓ', is 1.7 times PFL length, ℓ), the effect was apparent if: (1) $\tau_1 \sim \ell/c$, where τ_1 is CPL switch risetime, and (2) $\tau_2 << \ell/c$, where τ_2 is the PFL switch risetime. But 3-D line effects are not included in our calculations. The PFL end structure must present a close-to-ideal open circuit to reflections for double bounce to be effective. The flapper plates are designed to help meet this requirement by acting as "waveguides." Experiments to test the concept on EAGLE are planned.

Summary

In addition to the design and construction of EAGLE itself (see Figure 11), the EAGLE program has developed the conceptual design for ROULETTE, tested a low-inductance, high-energy-density Marx generator, developed an improved spark gap, demonstrated < 2 ns jitter from a 3 MV triggered gas switch, and designed and built an immersible, fiber-optic-coupled trigger system. Also, a significant development program in modular insulator technology has been conducted.

The insulator technology development (described elsewhere in these proceedings)[28] was undertaken to demonstrate that ROULETTE could be "modularized" at the water-vacuum interface. As part of that effort, a novel, racetrack-shaped insulator, shown in Figure 10, was developed and tested. This insulator, a half-scale prototype for EAGLE, is made by bonding cast urethane directly to aluminum to form a vacuum-tight seal. The development has been highly successful. The prototype tube is mechanically strong and has a demonstrated electrical breakdown strength equivalent to that of conventional insulators. Further development work using this concept is planned for EAGLE.

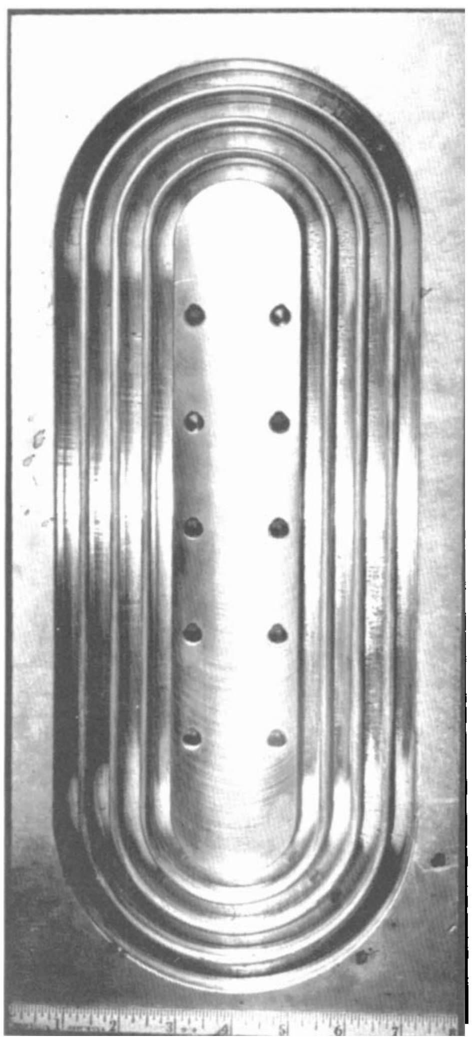

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Figure 10 Racetrack-shaped, cast-gradient-ring insulator developed for the EAGLE program.

EAGLE's first shot was fired on 1 May 1981. At this writing, experiments are being conducted on the eight-stage gas switch, and the optically-activated trigger system. Future experiments are planned in water triplate circuit optimization, water switching, water-breakdown-limited power flow (at full ROULETTE levels of linear current density), vacuum magnetic insulation and power flow, insulation flashover, and vacuum convolute techniques.

EAGLE is solely dedicated to pulsed power research. Our primary objective is to collect a firm data base for the design of ROULETTE. But EAGLE's versatility will permit its use in more general experiments for many years to come.

Acknowledgements

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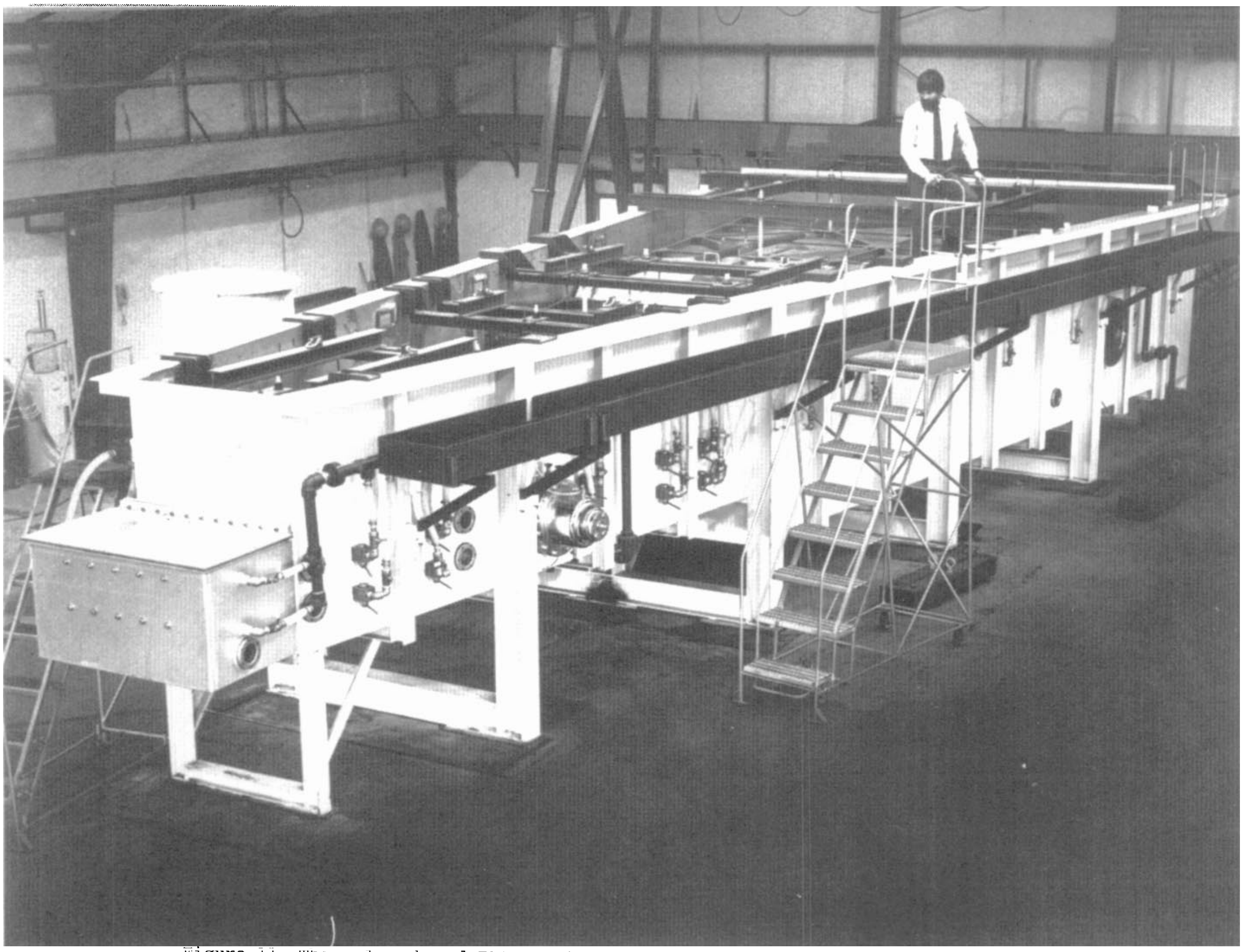

Figure 11 The wedge-shaped EAGLE module is 1/20th of PI's ROULETTE design. Nineteen other modules, now in the conceptual stage, will be combined with EAGLE to generate simultaneous pulses. The pulses will merge at the center of ROULETTE.